Very Long Baseline Neutrino Oscillations

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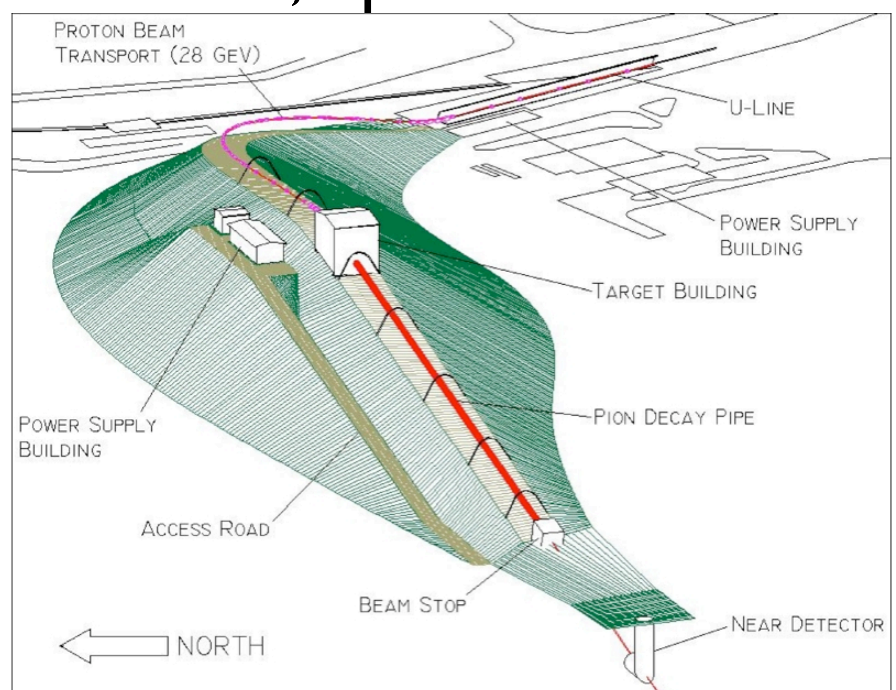
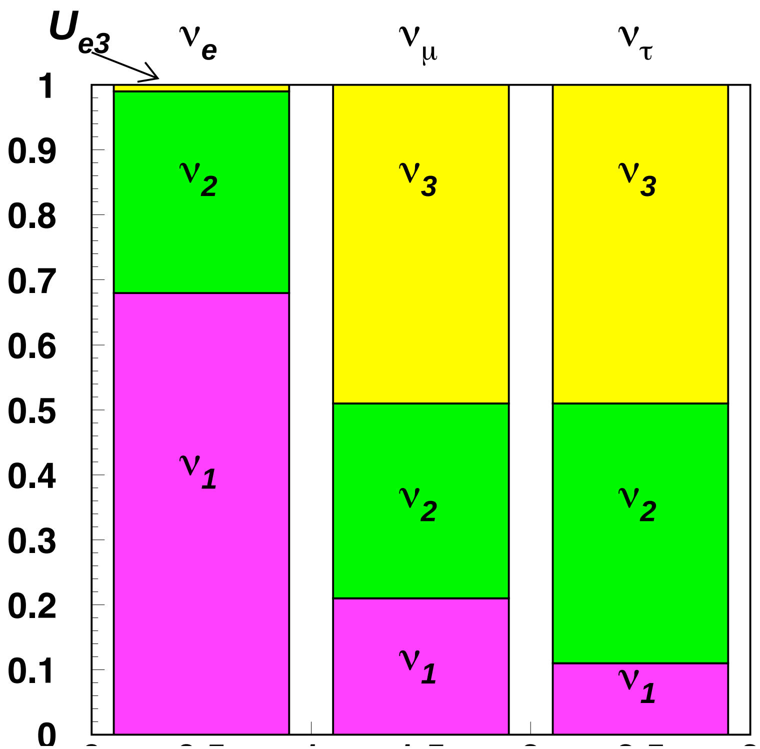
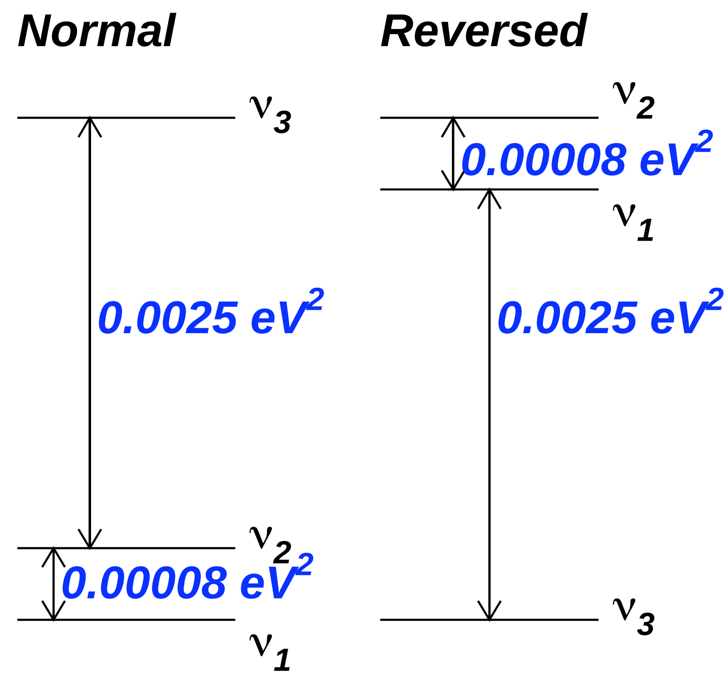
Annual DOE program review, April 2005



3 Generation oscillations





Difference in mass squares: $(m_2^2 - m_1^2)$

2-nu: $$P(\nu_a \to \nu_b) = \sin^2 2\theta \sin^2 \frac{1.27((m_2^2 - m_1^2)/eV^2)(L/km)}{(E/GeV)}$$

3-nu:
CP phase

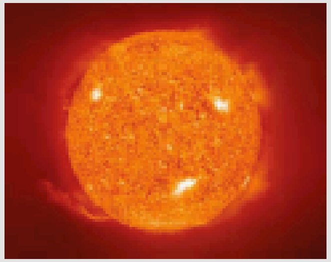
$$\begin{aligned} P(\nu_a \to \nu_b) \;=\; & \textstyle\sum_i |U_{ai}|^2 |U_{bi}|^2 \\ & + 2Re(U_{a1}^* U_{b1} U_{a2} U_{b2}^* \times exp(-i\Delta m_{21}^2 L/2E) \\ & + 2Re(U_{a1}^* U_{b1} U_{a3} U_{b3}^* \times exp(-i\Delta m_{31}^2 L/2E) \\ & + 2Re(U_{a2}^* U_{b2} U_{a3} U_{b3}^* \times exp(-i\Delta m_{32}^2 L/2E) \end{aligned}$$

no matter effects

Oscillation nodes at $\pi/2, 3\pi/2, 5\pi/2, \ldots$ $(\pi/2)$: $\Delta m^2 = 0.0025 eV^2$, $E = 1GeV$, $L = 494km$.

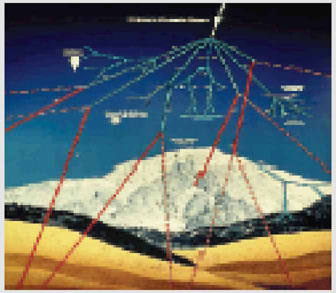
Solar : L~15000km

Neutrino Oscillations Results



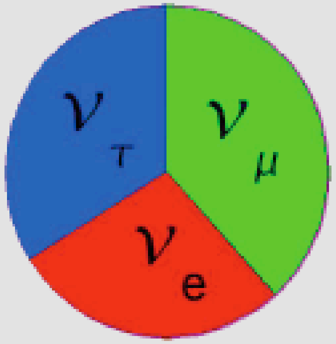
$$\Delta m^2_{21} = (8.0 \pm 0.3)\, 10^{-5}\, eV^2$$

$$\sin^2 2\theta_{12} = 0.86 \pm 0.04$$



$$|\Delta m^2_{32}| = (2.5 \pm 0.3)\, 10^{-3}\, eV^2$$ sign?

$$\sin^2 2\theta_{23} = 1.02 \pm 0.04$$ degeneracy?



$$\sin^2 2\theta_{13} < 0.12$$ (99% C.L.)

$$\delta_{CP} = ???$$

Values from: A. Strumia & F Vissani
hep-ph/0503246 - ifup-th/2005-06

Next Generation Experiments

- increase sensitivity $\sin^2 2\theta_{13}$ & δ_{CP} significantly
- precision measurements of Δm^2_{32} & $\sin^2 2\theta_{23}$
- resolve mass hierarchy (sign of Δm^2_{32})
- sensitive to new physics

The heart of the 3 generation picture needs an appearance experiment with L/E that includes effects from both mass differences. This implies baseline > 2000 km

- 28 GeV protons. 1 MW beam power. Horn focussed
- 500 kT water Cherenkov detector.
- baseline > 2500 km. WIPP, Henderson, Homestake
- We have proven by 3 years of work that this can be done.

Working group chronology

- December, 2001: Tom Kirk gave us a charge to form a working group.
- ~50 Members from Physics department, CAD, and outside universities.
    - Coordinators: W. Marciano (physics), M.Diwan(simulations), W. Weng(accelerator upgrade)
- BNL HENP PAC (2002)
- Internal AGS review (June 2004)
- HEPAP facilities plan(2003), Absolutely central (super-beam and large detector included in the the 20 yr outlook plan)
- APS neutrino study (2004)(proton driver recommendation)
- NESS workshop(Sep 2002), DUSEL S1(MVD is one of the working group leaders) and S2 workshops, 3 BNL/UCLA workshops(Dec 2003, May 2004, Feb 2005)

Working group written material

partial list

W. J. Marciano, "Long baseline neutrino oscillations and leptonic CP violation," Nucl. Phys. Proc. Suppl. **138**, 370 (2005).

M. V. Diwan, "The case for a super neutrino beam," Heavy Quarks and Leptons Workshop 2004, San Juan, Puerto Rico, 1-5 Jun 2004. arXiv:hep-ex/0407047.

J. Alessi, et al., "The AGS-based Super Neutrino Beam Facility, Conceptual Design Report," BNL-73210-2004-IR, 1 Oct. 2004.

W. T. Weng *et al.*, J. Phys. G **29**, 1735 (2003).

W. J. Marciano, "Extra long baseline neutrino oscillations and CP violation," BNL-HET-01-31, Aug 2001. 11pp. arXiv:hep-ph/0108181.

M. V. Diwan *et al.*, "Very long baseline neutrino oscillation experiments for precise measurements of mixing parameters and CP violating effects," Phys. Rev. D **68**, 012002 (2003) [arXiv:hep-ph/0303081].

+ numerous conference proceeding and working group reports.

We are after the science and facilities absolutely central to the US HEP program: Neutrino super beam and a large capable underground detector.

Why Very Long Baseline?

observe multiple nodes in oscillation pattern

☞ less dependent on flux normalization

neutrino travels larger distance through earth

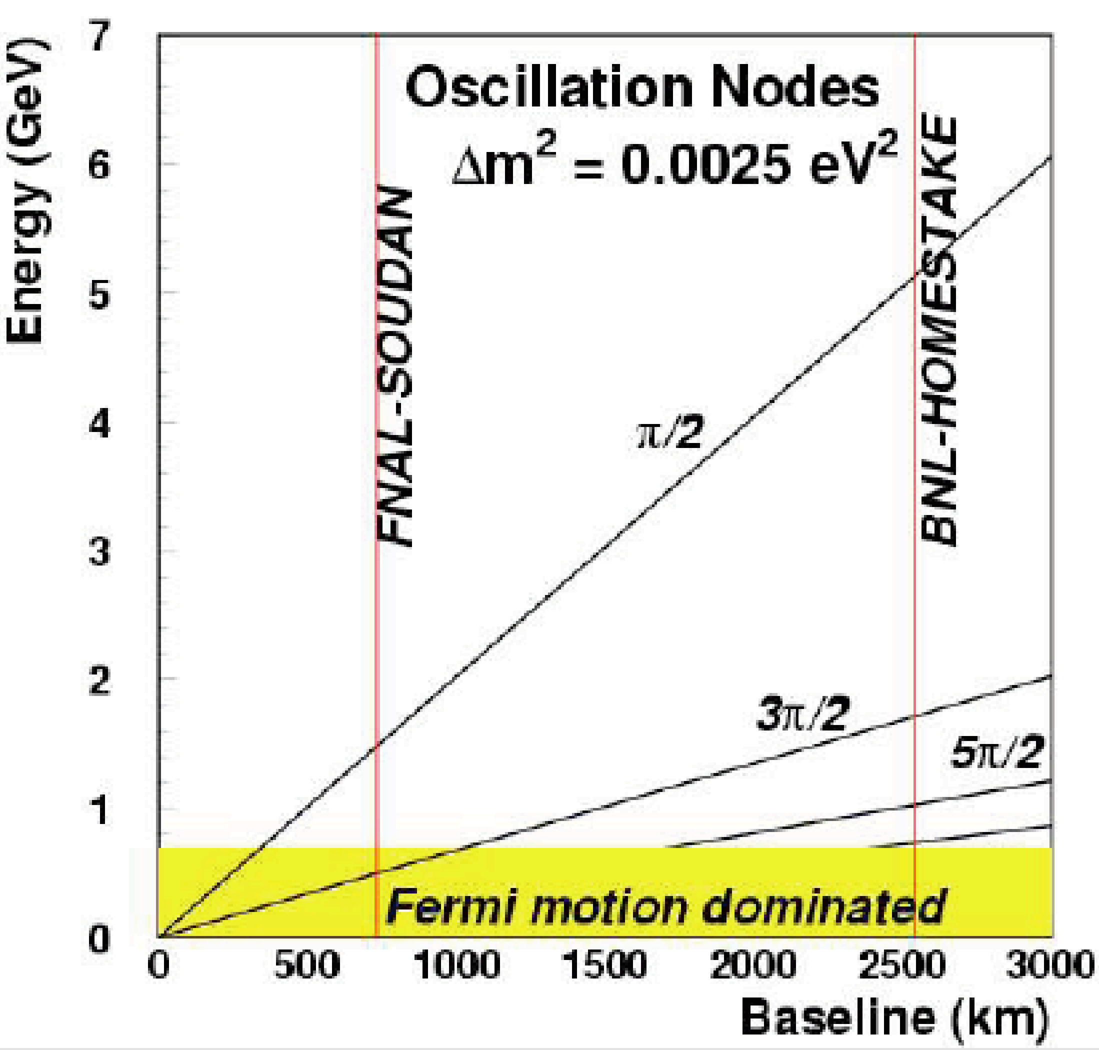
larger matter effects

flux ~ L^{-2}: lower statistics

but: CP asymmetry ~ L

sensitivity to δ_{CP} independent of distance!

better S:B



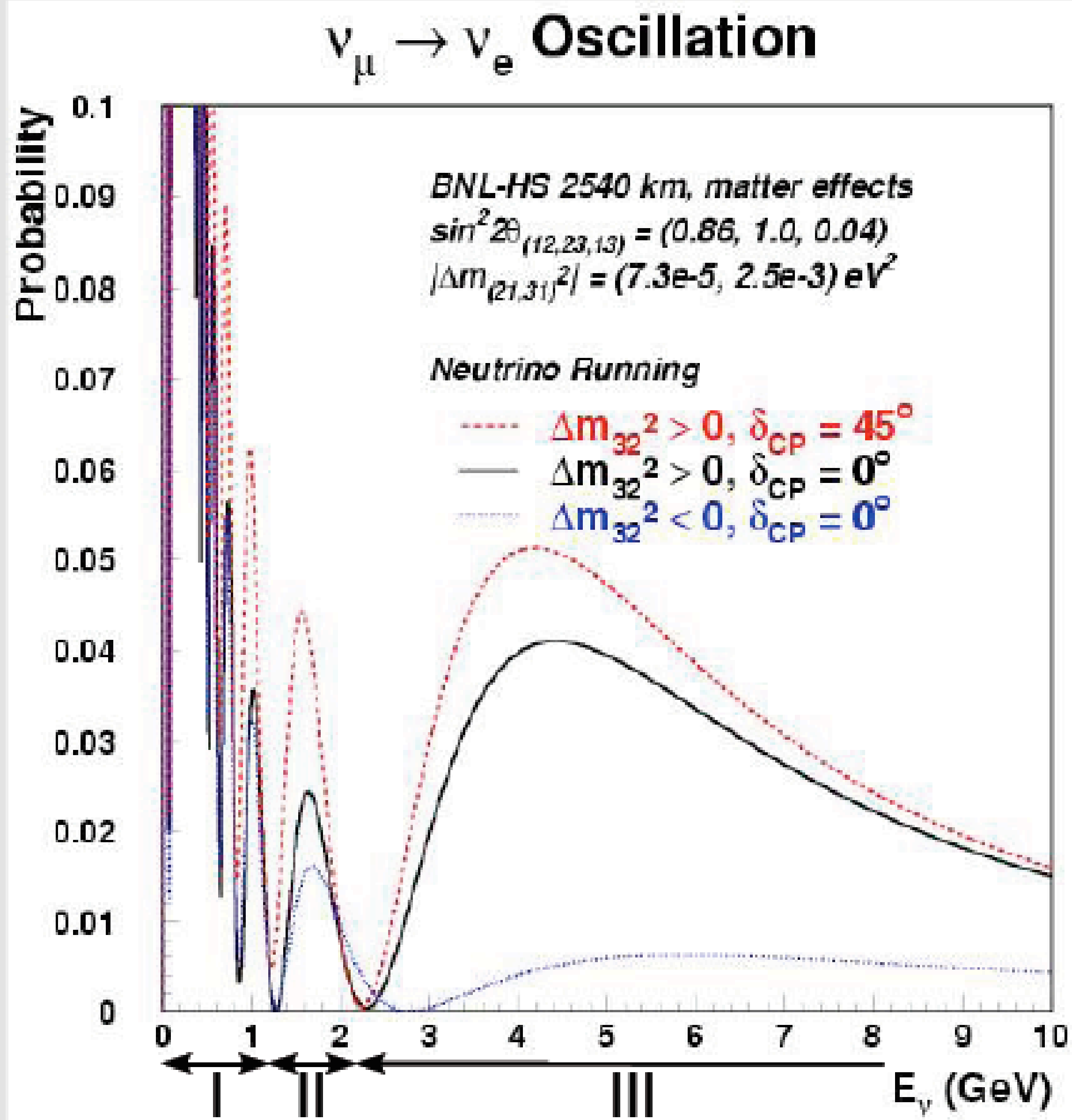
(Marciano hep-ph/0108181)

Why Broadband Beam?

observe multiple nodes extraction of oscillating signal from background.

- larger energies
  - larger cross sections
  - less running time for anti-neutrinos
- Sensitive to different parameters in different energy regions:

	I	II	III
$\sin^2 2\theta_{13}$	+	+	+
$\mathrm{sign}(\Delta m^2_{32})$	0	0	++
δ_{CP}	+	++	+
solar	++	+	+

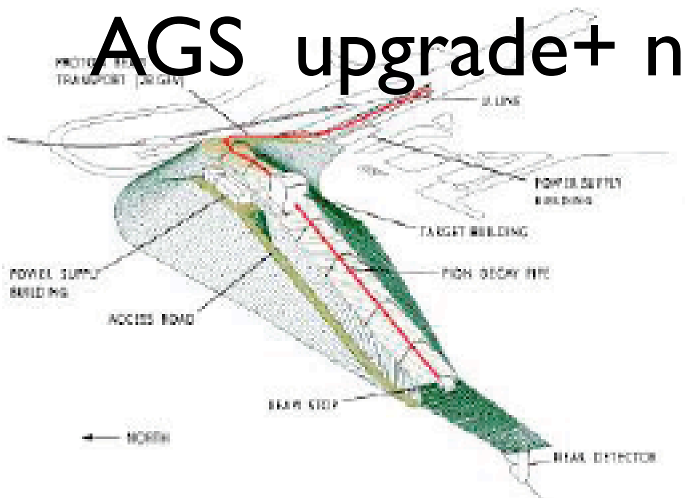


AGS Conceptual Design Report

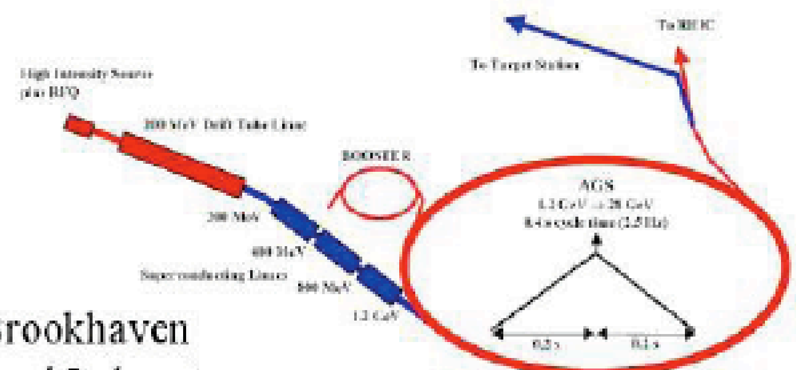
BNL-73210-2004-IR

The AGS-Based Super Neutrino Beam Facility
Conceptual Design Report

AGS upgrade+ new beam = $273M + burdens



details in D.L.'s talks



Brookhaven
National Laboratory
Upton, NY 11973
8 October 2004

October 8, 2004 BNL-73210-2004-IR

The AGS-Based Super Neutrino Beam Facility
Conceptual Design Report

Editors: W. T. Weng, M. Diwan, and D. Raparia

Sent to DOE Oct 2004

Contributors and Participants

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BNL-73210-2004-IR

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October 8, 2004

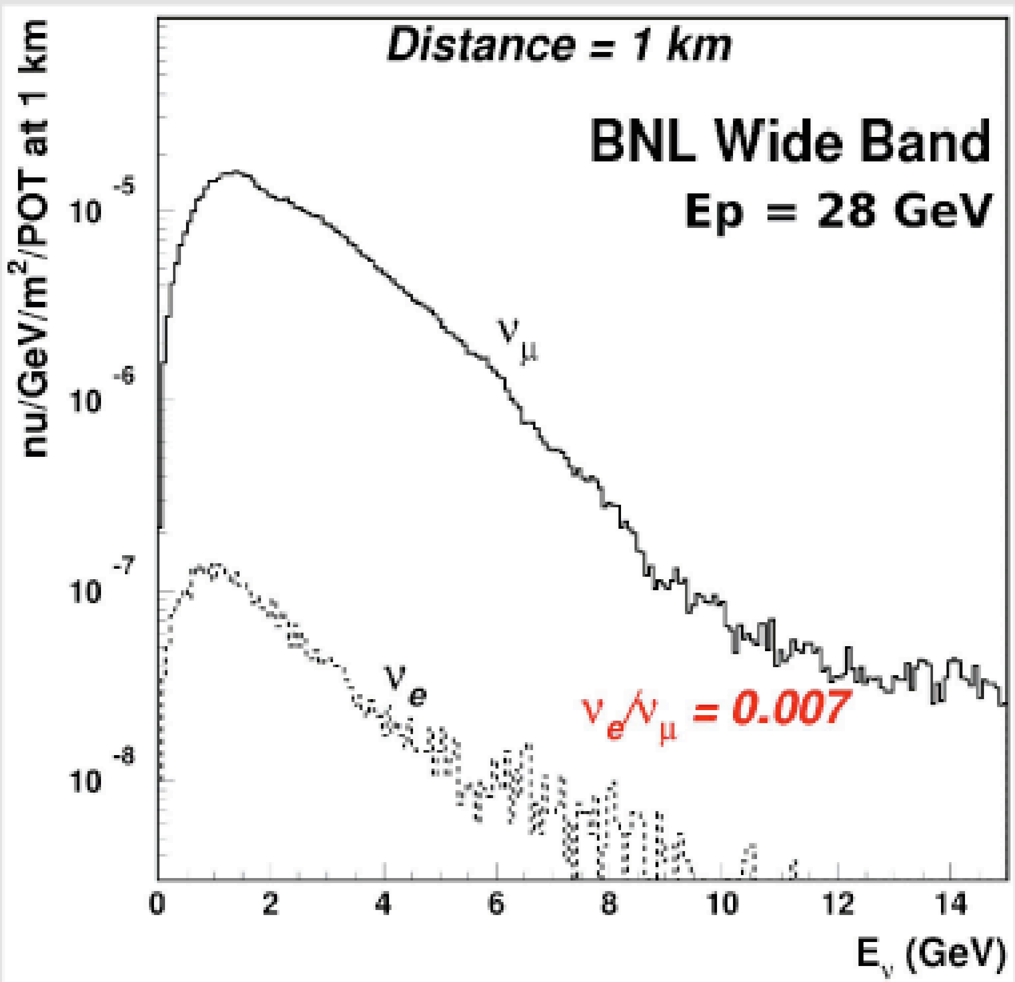
http://raparia.sns.bnl.gov/nwg_ad/agsnbcdr1.pdf

AGS 1MW proton beam

Upgrade AGS (28 GeV protons)

intensity: $7.10^{13} \rightarrow 9.10^{13}$ ppp

rep. rate: ~0.3Hz → 2.5Hz



1) ramp time: ~1.2s → 0.2s
   repl. power supply, rf, ...

2) filling time: 0.6s → 1ms
   replace booster:
   extend warm linac 200 MeV
   new SC linac 1 GeV

3) Work continues to goto 1.5 or 2 MW.

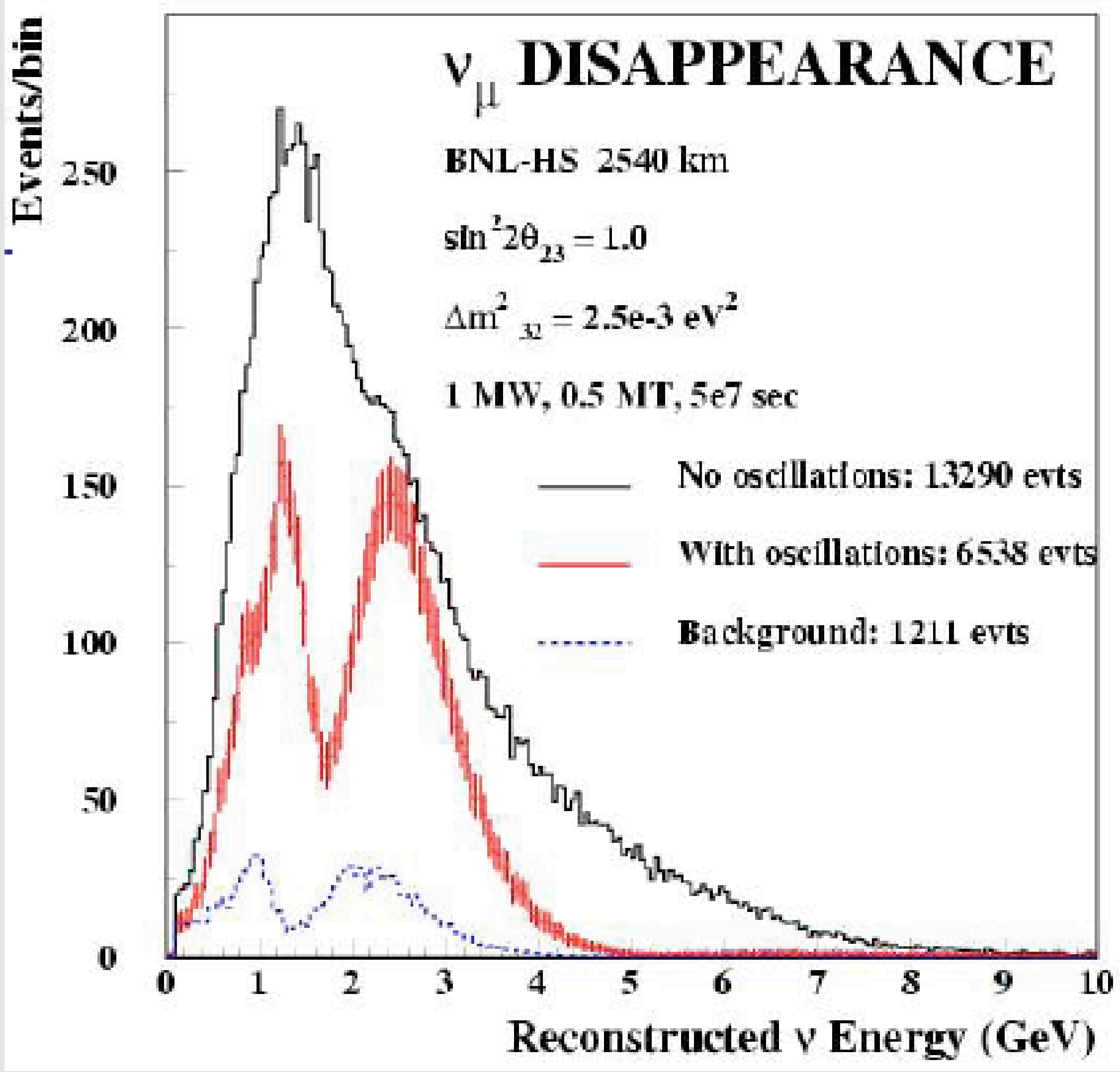
4) Experimental work on 1 MW carbon-carbon target.

ν_μ disappearance

<u>neutrino running:</u>

1MW beam
0.5Mt water Cerenkov det.
2540km distance
5e7s running time
~50000 tot CC events

determine Δm^2_{32}
& $\sin^2 2\theta_{23}$ to 1%
systematics dominated



<u>anti-neutrino running:</u>

same as ν but with
2MW beam

including anti-ν running:
- CPT test possible
- errors below 1% achievable

ν_e Appearance

backgrounds:

- beam ν_e
- NC ν_μ

neutrino running:

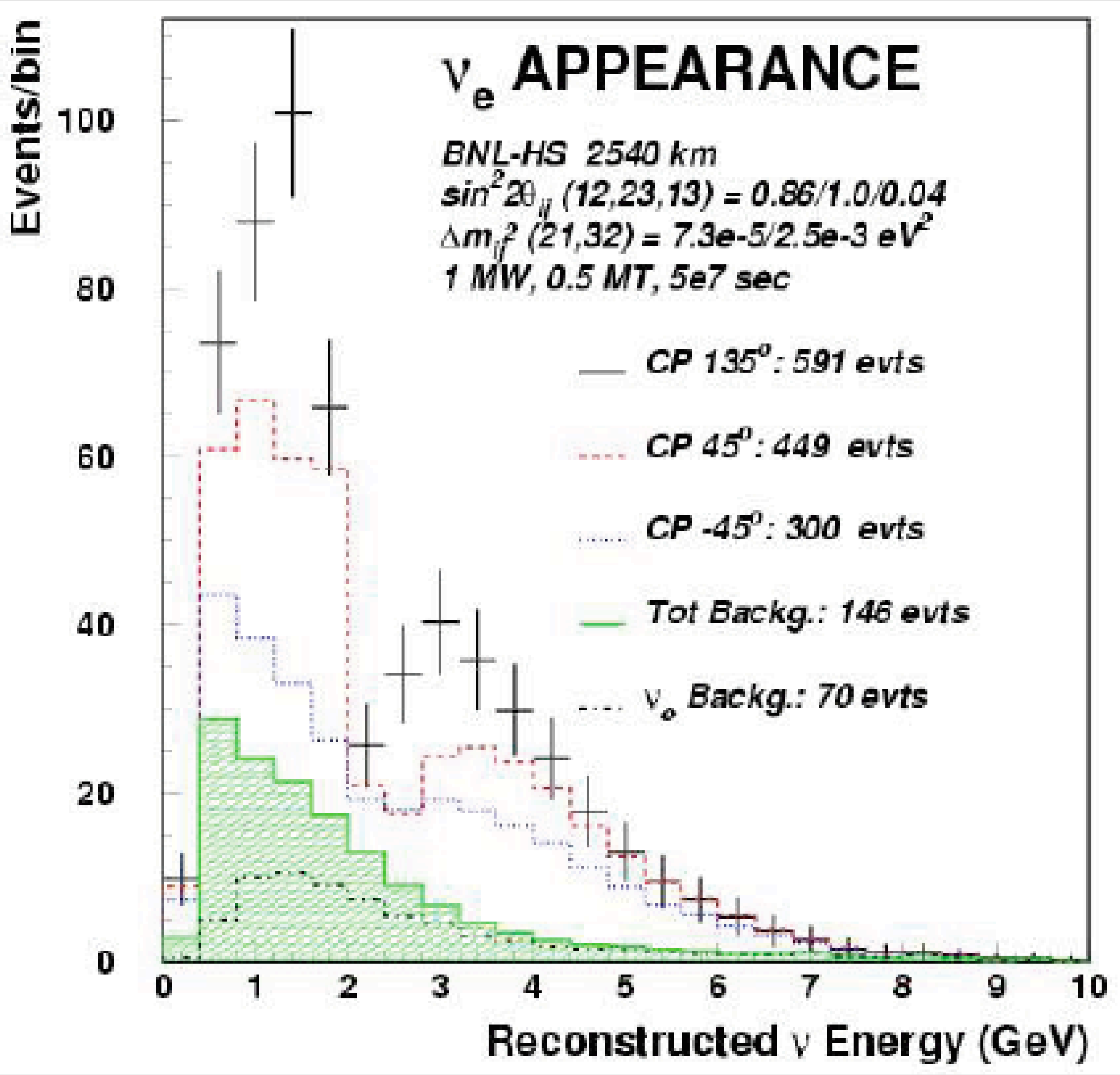
measure $\sin^2 2\theta_{13}$ and δ_{CP}

for $\sin^2 2\theta_{13} > 0.01$

resolve mass hierarchy

include anti-neutrino run:

exclude $\sin^2 2\theta_{13} > 0.003$



if $\sin^2 2\theta_{13}$ too small → δ_{CP} measurement not possible

observation ν_e appearance possible through solar term

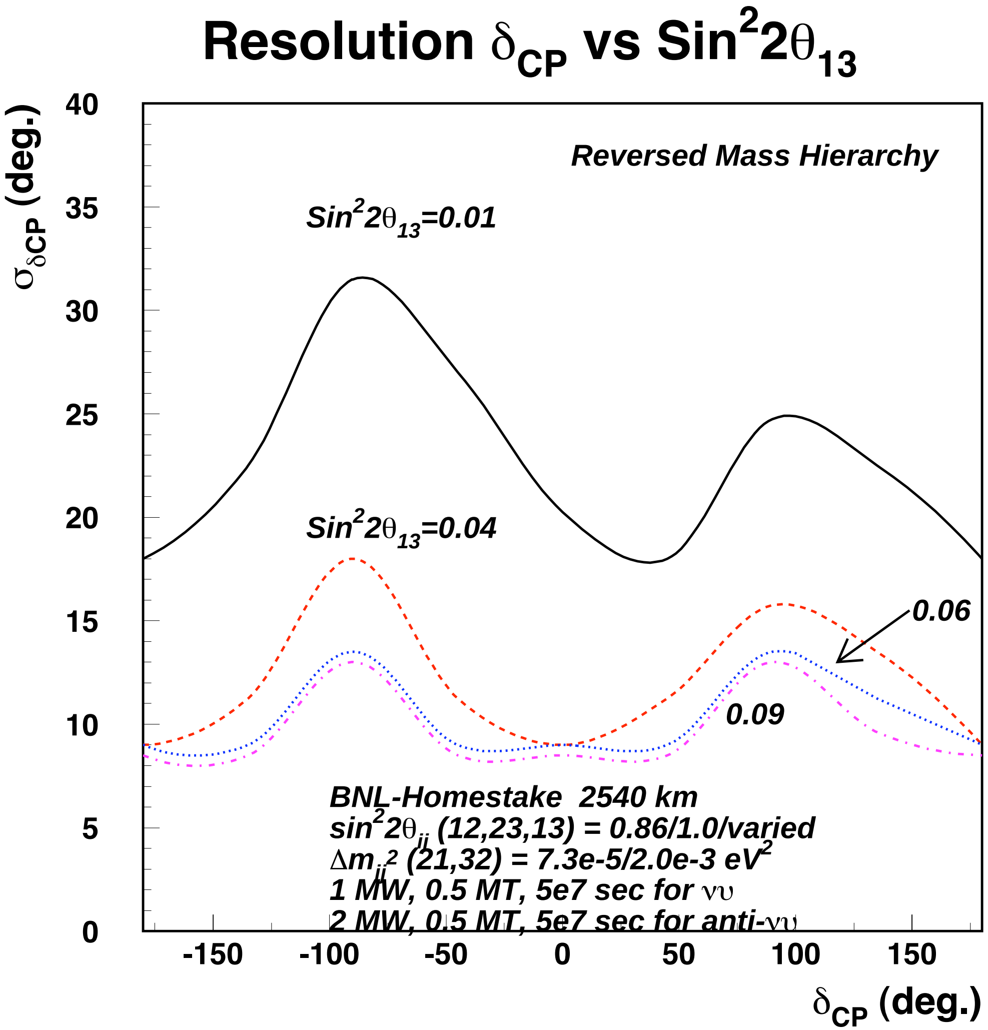
Status of physics work

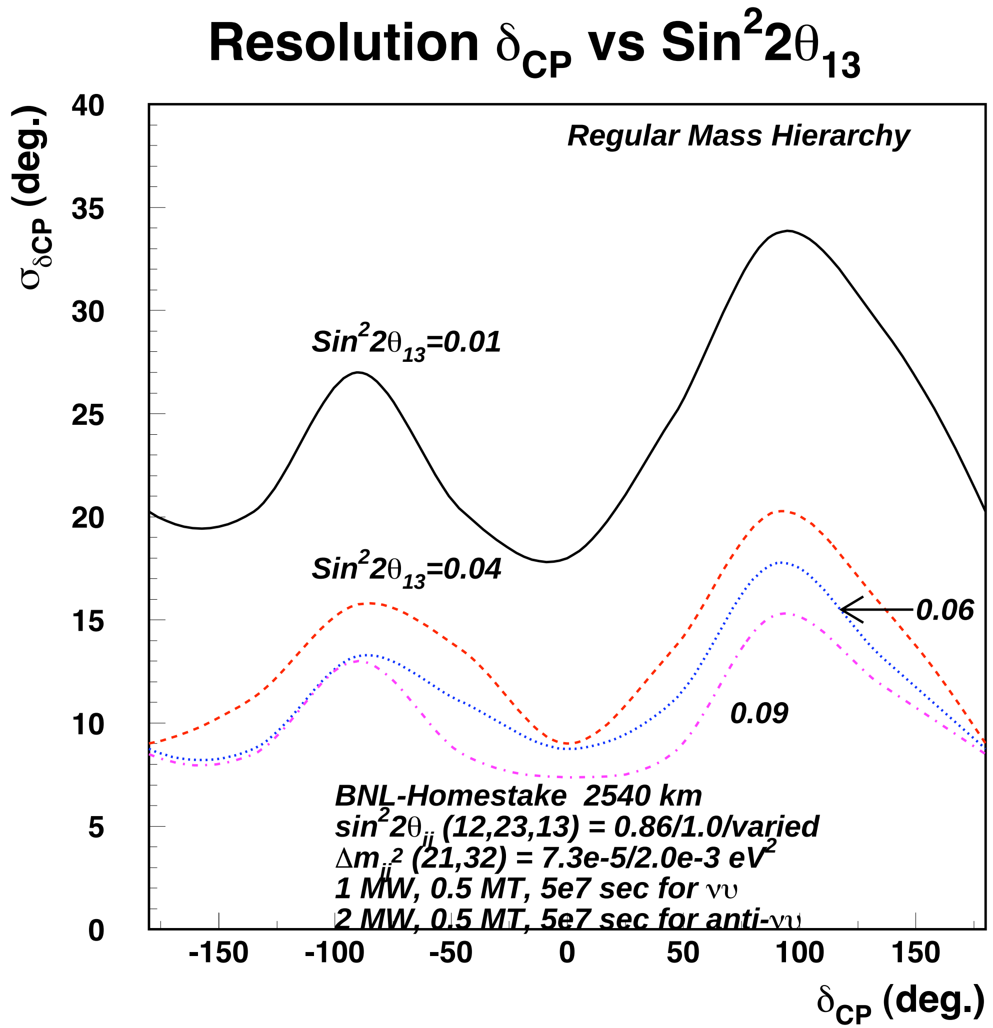
- With neutrino and anti-neutrino running can resolve mass hierarchy to 10 sigma, measure CP violation, and look for new effects.
- Have examined more detailed issues regarding baseline. Optimization based on physics judgement. But longer baseline => better science.

M. Diwan, Proc. Heavy Quarks and Leptons, hep-ex/0407047

- GREAT PROGRESS ON DETECTOR BACKGROUNDS !

CP resolution





More than 10 sigma resolution of mass hierarchy after anti-neutrino running and excellent resolution on delta-CP.

Detector

- 500 kT fiducial mass for both proton decay and neutrino astro-physics and neutrino beam physics.
- ~10% energy resolution on quasielastic events.
- muon/electron separation at <1%
    - 1,2,3 track event separation.
    - Showering NC event rejection at factor of ~20.
- Low threshold (~5 MeV) for solar and supernova physics.
- Time resolution ~few ns for pattern recognition and background rejection.

Previous issues being solved

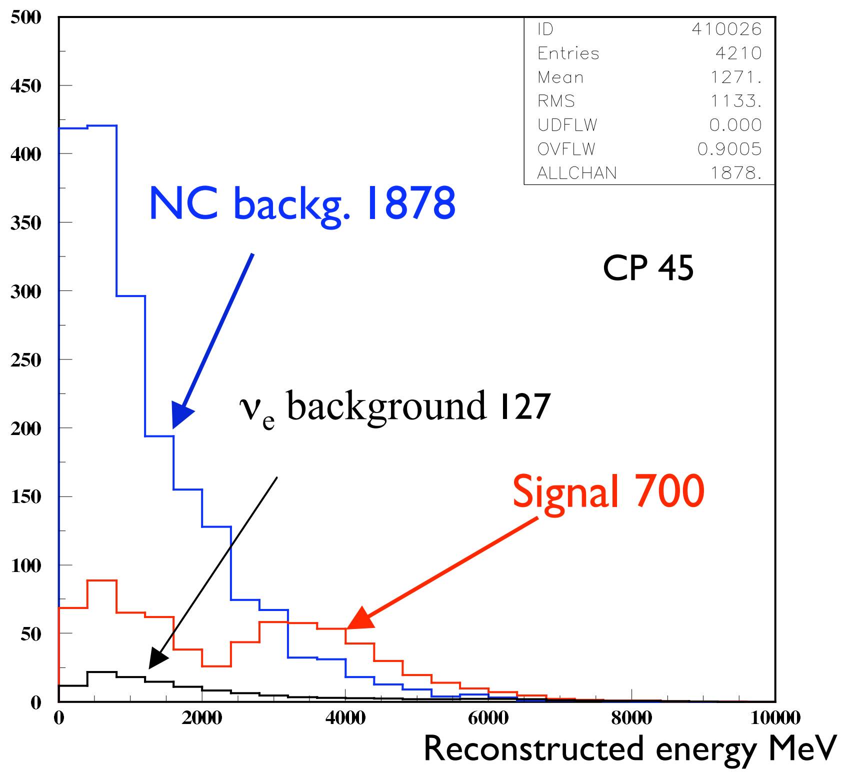
Water Cherenkov can satisfy these requirements

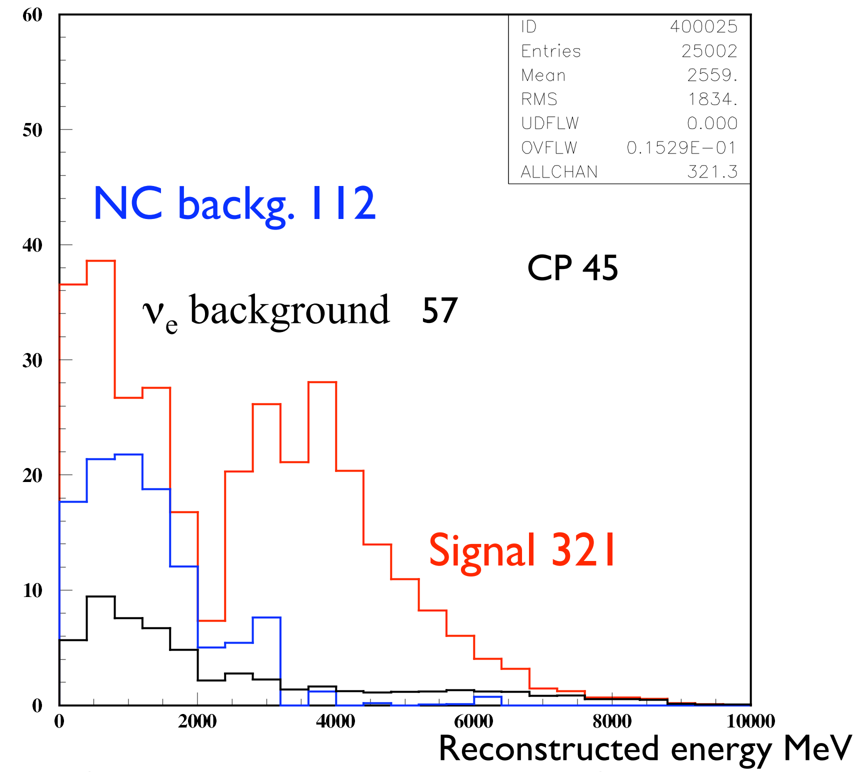
Not magic. Performance is obtained by giving up large fraction of potential signal CC events; and using the kinematics of NC events.

Complete water Cherenkov detector simulations progress

ν_e CC for signal ; all $\nu_{\mu,\tau,e}$ NC , ν_e beam for background

- Δm^2_{21} =7.3 x 10^{-5} eV^2, Δm^2_{31}=2.5 x 10^{-3}eV^2
- $\sin^2 2\theta_{ii}$(12,23,13)=0.86/1.0/0.04, δ_{CP}=+45,+135,-45,-135°





Select single ring events and select electrons

Signal/backg = 700/2005

Perform analysis of single electron pattern, likelihood cut retaining ~50% of signal.

Signal/back = 321/169

C. Yanagisawa (Stony Brook), 3rd BNL/UCLA workshop
http://www.physics.ucla.edu/hep/proton/proton2005.htm

Scientific Reach of Future Neutrino Oscillations Exps.

Parameter	T2K	T2HK	Reactor	Nova	Nova2	VLBNO
Δm_{32}^2	✓	✓	-	✓	✓	✓
$\sin^2(2\theta_{23})$	✓	✓	-	✓	✓	✓
$\sin^2(2\theta_{13})$ [a]	✓	✓	✓	✓	✓	✓
$\Delta m_{21}^2 \sin(2\theta_{12})$ [b]	-	-	-	-	-	12%
sign of (Δm_{32}^2) [c]	Nova	-	-	T2K	T2K	yes
measure δ_{CP} [d]	-	Nova	-	-	T2HK	±13°
N-decay improv.	x1	x20	-	-	-	x10
Detector (KTons)	50	1000	20	30	30	500
Beam Power (MW)	0.74	4.0	14000	0.65	2.0	1.0
Baseline (km)	295 [e]	295 [e]	1	810 [e]	810 [e]	>2500
Detector Cost ($M)	exists	~$$$	20	165	+ ???	$$
Beam Cost ($M)	exists	$$	exists	$	$$$	400

Combined measurement

[a] detection of $\nu_\mu \rightarrow \nu_e$, upper limit on or determination of $\sin^2(2\theta_{13})$

[b] detection of $\nu_\mu \rightarrow \nu_e$ appearance, even if $\sin^2(2\theta_{13}) = 0$; determine θ_{23} angle ambiguity

[c] detection of the matter enhancement effect over the entire δ_{CP} angle range

[d] measure the CP-violation phase δ_{CP} in the lepton sector; Nova2 depends on T2HK

[e] beam is 'off-axis' from 0-degree target direction

Comments on Neutrino Oscillations Experiments

- *All* parameters of neutrino oscillation can be measured in *one* experiment
  - a Very Long Baseline Neutrino Oscillation (VLBNO) at >2000 km
  - the cost of VLBNO is comparable to (or less than) competing proposals
  - the mass of the VLBNO target enables a powerful *Nucleon Decay* search
- Use of a *broadband neutrino beam* at *very long distances* is the key
  - Oscillatory signal very important for extracting signal from background and measuring parameter without systematics.
- Focus on CP because **The CP-violation parameter is the most difficult parameter to determine**
  - matter effects interact with CP-violation effects
  - the CP-violation phase δ_{CP} has distinct effects over the full 360^{o} range
- **Off-axis beam method requires multiple distances and detectors to get same science.**
  - each step in offaxis will require of order 10 Snomass years of running
- **All measured oscillation parameters will be limited to ~1% precision by systematic errors except $\sin^2(2\theta_{23})$**

R&D Request

- Resources to lower costs of the AGS upgrade and neutrino super beam.
- Must push 1 MW target studies to completion.
- Resources to push water Cherenkov simulations as well as start detector R&D.
- We have 4 university groups working closely with us. Need more.
- Support for visiting scientists, students needed.

Conclusions

- Powerful new method for neutrino CP violation study. Absolutely central part of the HEP facilities plan and the APS neutrino study plan.
- We have made great progress on many technical issues.
- Important work performed on detector background issue.
- Need encouragement, resources, and time to make a complete experimental proposal.
- Meanwhile, EXPECT A DETECTOR R&D PROPOSAL SOON.